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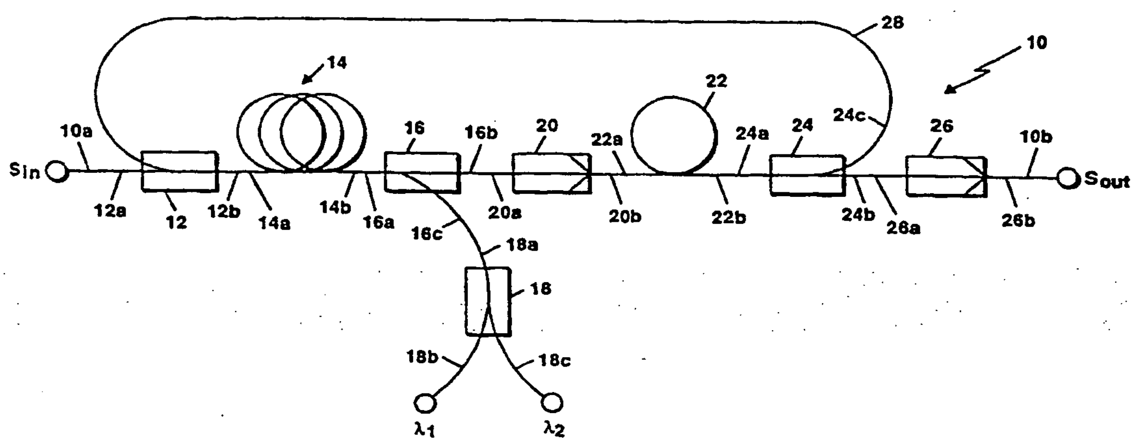


(57) Abstract

A multiple stage optical amplifier includes a Raman fiber amplifier first stage coupled to a rare earth doped fiber amplifier which provides a second amplifier stage. Pump signals with two wavelengths are injected into the Raman amplifier and propagate in a direction opposite to input signals. Since the Raman amplifier does not completely absorb the pump signals, a separate optical path is provided to apply the excess pump signal to the second stage fiber amplifier to pump it. The gain and banwidth characteristics of the Raman amplifier are determined by the spectral properties of the pump signal and gain bandwidth characteristic of the Raman amplifier can be selected by appropriately selecting the wavelengths of the pump signals. In one embodiment, the pump signals are selected so that the first stage Raman amplifier has a relatively low noise characteristic. The second stage fiber amplifier, on the other hand, is designed to have a relatively high power characteristic. Furthermore, to increase the gain bandwidth of the entire optical amplifier, the gain bandwidth characteristics of the first and second amplifier stages are selected to overlap rather than coincide.

MULTIPLE STAGE OPTICAL FIBER AMPLIFIER

FIELD OF THE INVENTION

This invention relates generally to optical fiber amplifiers and, more particularly to, low noise, high power optical fiber amplifier circuits.

BACKGROUND OF THE INVENTION

As is known in the art, an optical amplifier is a device that increases the amplitude of an input optical signal fed thereto. If the optical signal at the input to such an amplifier is monochromatic, the output will also be monochromatic, with the same frequency. A conventional fiber amplifier comprises a gain medium, such as a single mode glass fiber doped with a rare earth material, connected to a WDM coupler which provides low insertion loss at both the input signal and pump wavelengths. The input signal is provided, via the coupler, to the medium. Excitation occurs through optical pumping from the pumping source, which is combined with the optical input signal within the coupler, which is within the absorption band of the rare earth dopant, and an amplified output signal is emitted from the other end of the fiber.

Such amplifiers are typically used in a variety of applications including but not limited to amplification of weak optical pulses such as those that have traveled through a long length of optical fiber in communication systems. Optical amplification can take place in a variety of materials including those materials, such as silica, from which optical fibers are formed.

One type of fiber amplifier referred to as an erbium (Er) amplifier typically includes a silica fiber having a single-mode core doped with erbium (specifically doped with erbium ions conventionally denoted as Er^{3+}). It is well known that an erbium optical fiber amplifier operating in its standard so-called three level mode is capable, when pumped at a wavelength of 980 nanometers (nm), of amplifying optical signals having a wavelength of approximately 1.5 micrometers (μm). Since 1.5 μm is the lowest loss wavelength of conventional single-mode glass fibers, erbium

amplifiers are well suited for inclusion in fiber systems that propagate optical signals having wavelengths around 1.5 μm.

However, there are several limitations with erbium fiber amplifiers used in practical communication systems. One problem is that is that the gain characteristic is relatively uniform only within a relatively narrow gain bandwidth. In addition, the output power characteristic developed by erbium amplifiers is limited by the range of power available from pump sources used to pump the fiber. Also, with the advent of dense wavelength division multiplexed (WDM) systems, the available gain bandwidth and uniformity of gain flatness has become a critical issue in optical amplifier design.

Another type of well-known optical fiber amplifier is a so-called Raman amplifier. A Raman amplifier provides amplification of signals, via stimulated Raman scattering in an optical fiber, and does not have the gain bandwidth problems associated with erbium amplifiers. One problem with Raman amplifiers, however, is that they are relatively inefficient and thus must be pumped with pump signals having relatively high power levels in order to obtain suitable output power. Much of the energy from the high power pump signals is not utilized and becomes wasted and, even when pumped with high power pump signals, the Raman amplifier provides output signals having relatively low power levels due to the inefficient use of the energy provided by the pump signal. This is especially true when the Raman amplifier is not operated in its "saturation mode".

Another problem with Raman amplifiers is that the upper atomic energy level of the amplifier has essentially a zero lifetime. In a wave division multiplexed system, the rapid depletion of the upper amplifier energy level can result in crosstalk between the required high power pump signal and an input signal to be amplified.

It would therefore be desirable to provide an optical fiber amplifier having a relatively wide bandwidth, a relatively low noise characteristic and a relatively high output power characteristic.

SUMMARY OF THE INVENTION

In accordance with the present invention, a multiple stage optical amplifier includes a first fiber amplifier stage optically coupled to a second fiber amplifier stage. In accordance with one embodiment, a pump signal is injected into the first amplifier stage at the connection between the first and second stages and propagates in a direction opposite to the input signals. The first amplifier stage does not completely absorb the pump signal so that it does not saturate and an optical path may also be provided to apply the excess pump signal to the second amplifier stage to pump it. The optical path is arranged so that the pump signal also propagates in a direction opposite to input signals in the second amplifier stage.

In accordance with another embodiment, a pump signal is injected into the second amplifier stage and propagates in a direction opposite to input signals. The second amplifier stage does not completely absorb the pump signal and a separate optical path is provided to apply the excess pump signal to the first amplifier stage to pump it. The pump signal also propagates in a direction opposite to input signals in the first amplifier stage.

In accordance with still another embodiment, the first fiber amplifier stage is a Raman amplifier and the second amplifier stage is a rare earth doped fiber amplifier. The gain and bandwidth characteristics of the Raman amplifier stage are selected by choosing the wavelengths of the pump signals so that the Raman amplifier stage has a relatively low noise characteristic. The rare earth doped amplifier stage, on the other hand, is designed to have a relatively high power characteristic. Furthermore, to increase the gain bandwidth of the entire optical amplifier, the gain bandwidth characteristics of the first and second amplifier stages are selected to overlap rather than coincide.

For example, the wavelengths of the pump signals may be selected such that the gain characteristic provided by the Raman amplifier stage complements the gain characteristic of the rare earth doped amplifier stage . This provides an amplifier having a high gain characteristic and a low noise characteristic over a relatively wide bandwidth. In addition, the power levels of the pump signals may be selected such that the Raman amplifier operates

in an unsaturated amplifier mode. Since the Raman amplifier does not efficiently use all of the power of the pump signals, the excess pump signal power from the Raman amplifier stage pumps the rare earth doped amplifier. Thus the consequences of the inefficiency of the Raman amplifier are minimized since the pump signals are recycled to pump the rare earth amplifier.

Moreover, the pump signals are arranged to propagate through the Raman amplifier stage and the rare earth doped amplifier stage in a direction which is opposite to the direction in which the input signal propagates through the amplifier stages. This minimizes crosstalk between the input signal and the pump signals. Such minimization of crosstalk results because the walk-off characteristic between the input signal and pump signal is large and, accordingly, the pump-mediated signal crosstalk mechanism is thus defeated.

In one embodiment, the rare earth doped amplifier stage may use an erbium-doped silica fiber or, in an alternate embodiment, an erbium-doped fluoride fiber. Since a fluoride fiber provides amplification to signals having relatively long wavelengths, use of a fluoride fiber may increase the overall amplifier gain bandwidth. In another embodiment, two pump signals having wavelengths of 1435 nm and 1465 nm, respectively, are used to pump the Raman amplifier stage. This approach results in the optical amplifier having a relatively wide and flat gain characteristic with a gain bandwidth of 50 nm or greater.

In yet another embodiment, two pump frequencies are used to pump the multiple stage amplifier.

In still another embodiment, a single pump source is used to pump the Raman amplifier stage. The pump source may be a Raman fiber laser which provides an output signal having a wavelength typically of about 1480 nm. Alternatively, the single pump source may be provided as two high-power diodes which provide an output signal having a wavelength typically of about 1480 nm.

In another embodiment, the first amplifier stage is an erbium doped fiber amplifier and the second stage is a Raman amplifier.

In another embodiment, the first amplifier stage is a fiber amplifier with a thulium doped ZBLAN core and the second stage is an erbium/ytterbium doped fiber amplifier. The first amplifier stage is cladding pumped from a 1.06 μm pump source.

In still another embodiment, the first amplifier stage is a fiber amplifier with a praseodymium doped ZBLAN core and the second amplifier stage is an erbium/ytterbium doped fiber amplifier. The first amplifier stage is cladding pumped from a 1.04 μm pump source.

BRIEF DESCRIPTION OF THE DRAWING

The foregoing features of the invention, as well as the invention itself may be more fully understood from the following detailed description of the drawing, in which

FIG. 1 is a block diagram of an optical amplifier constructed in accordance with the principles of the present invention with a Raman amplifier first stage and a rare earth doped second stage.

FIG. 2 is a block diagram of an optical amplifier constructed in accordance with the principles of the present invention with a rare earth doped first stage and a Raman amplifier second stage.

FIG. 3 is a plot of the gain spectrum of the multiple stage amplifier illustrated in FIGs. 1 and 2.

FIG. 4 is a block diagram of an optical amplifier constructed in accordance with the principles of the present invention in which the first amplifier stage is a fiber amplifier with a thulium doped ZBLAN core and the second stage is an erbium/ytterbium doped fiber amplifier.

FIG. 5. is a plot of the gain spectrum of the multiple stage amplifier illustrated in FIG. 4.

FIG. 6 is a block diagram of an optical amplifier constructed in accordance with the principles of the present invention in which the first amplifier stage is a fiber amplifier with a praseodymium doped ZBLAN core and the second stage is an erbium/ytterbium doped fiber amplifier.

FIG. 7 is a plot of the gain spectrum of the multiple stage amplifier illustrated in FIG. 6.

FIG. 8 is a block diagram of an optical amplifier constructed in accordance with the principles of the present invention in which the pumping signals are applied to the second amplifier stage.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring now to FIG. 1, an optical amplifier 10 having an input port 10a and an output port 10b includes a first wave division multiplexer (WDM) 12 having an input port 12a coupled to amplifier input port 10a. An output port 12b of WDM 12 is coupled to an input port 14a of a Raman fiber amplifier 14 which serves as a first amplifier stage of amplifier 10. Raman amplifier 14 has a quantum-limited noise figure which causes optical amplifier 10 to have a relatively low noise figure. Amplifier 14 is comprised of a cladded optical fiber which may be, for example, a germano-silica fiber having a core diameter typically in the range of about 2 μm - 5 μm and having an insertion loss characteristic not greater than 0.6 decibels per kilometer (db/km) at a wavelength of about 1480 nm. Also, when the fiber is to amplify radiation of wavelength λ_l, where $\lambda_l = \lambda_{i-1}, + \Delta\lambda_l$ in which $\Delta\lambda_i$ is a length within the appropriate Stokes band associated with the fiber, l=1, ... , n (n is an integer equal to or greater than 2) and λ_{l-1} is defined to be the wavelength λ_p of the pump radiation when l=1, a fiber having a relatively high value of delta is preferred.

Amplifier 14 is coupled to an input port of an erbium-doped fiber amplifier 22 through a second WDM 16 and a first isolator 20. Specifically, an output port 14b of amplifier 14 is coupled to an input port 16a of second WDM 16 and an output port 16b of WDM 16 is coupled to an input port 20a of isolator 20. Isolator 20 is provided having an isolation characteristic typically of about 40 dB. An output port 20b of isolator 20 is coupled to a first input port 22a of erbium-doped (Er) amplifier 22 which provides a second amplifier stage of amplifier 10.

Er amplifier 22 is provided from a single mode fiber section having a core doped with Er^{3+} ions using conventional doping techniques. Although, in a preferred embodiment, second stage amplifier 22 is an Er amplifier, it should be appreciated that amplifier stage 22 may alternatively be fabricated

from a single mode fiber having a core doped with a rare earth metal other than erbium. In addition, the fiber may be a silica glass fiber or, alternatively, fluoride glass compositions based on ZrF_4, for example ZBLA and ZBLAN, may also be used.

Amplifier stage 22 is pumped with a signal having a predetermined wavelength. The output of amplifier 22 is coupled to an input port 24a of a third WDM 24 and a first output port 24b of the WDM 24 is coupled to a second isolator 26 at an input port 26a. Isolator 26 may be provided, for example, as a multistage isolator having a relatively low insertion loss in a pass band which is at least as wide as the gain bandwidth provided by amplifier stages 14, 22. An output port 26b of isolator 26 is coupled to amplifier output port 10b.

A third WDM 18 has input ports 18a, 18b through which are fed respective ones of pump signals P_1, P_2 having respective wavelengths λ_1 and λ_2. An output port 18c of WDM 18 is coupled to a second input port 16c of WDM 16. Thus pump signals P_1, P_2 are fed through WDM 18 to input port 16c of WDM 16

The pump signals P_1, P_2 propagate through WDM 16 and pump Raman amplifier 14. An optical signal path 28 has a first end coupled to an output port of 12c of WDM 12 and a second end 28b coupled to a third port 24c of WDM 24.

In operation, pump signals P_1 and P_2 having respective wavelengths λ_1 and λ_2 pump the Raman amplifier 14 at a level which is below the saturation level of the amplifier 14. Thus, the excess pump power from the first unsaturated Raman amplifier stage 14 is coupled via signal path 28 through WDM 24 and fed to the second amplifier stage 22 to thus pump the Er amplifier 22.

Consequently, the pump signal energy not used in the first amplifier stage 14 is used in the second amplifier stage 22. Thus, the Raman amplifier 14 is intentionally not operated in saturation mode because it is desirable to make the pump power provided by pump signals, P_1 and P_2 , available to the second amplifier stage 22 where the pump power is used in a manner which is relatively efficient when compared with the efficiency with

which the Raman amplifier 14 uses the pump signal. In typical applications, the percentage of the pump power fed to Raman amplifier 14 which is coupled through signal path 28 to the second stage amplifier 22 is in the range of about 40% to 90% with typically about 75% of the pump power being preferred.

As mentioned above, Raman amplifiers are relatively inefficient and thus require pump signals having a relatively high power level. This is especially true when the Raman amplifier is not pumped at a level which drives the amplifier into its saturation region. Thus, by utilizing signal path 28 to couple the pump power from the first amplifier stage to the second amplifier stage, the inefficiency and high power pump signal requirement of the Raman amplifier is mitigated.

Moreover, since the pump signal propagates through the Raman amplifier in a direction which is opposite that of the input signal, crosstalk between the pump signal and the input signal is minimized. This is due to the fact that the walk off between the input signal and pump signal is relatively large and thus pump-mediated signal crosstalk is reduced.

The gain and bandwidth characteristics of the Raman amplifier are determined by the spectral properties of the pump signal. Thus, the Raman amplifier can be designed to have preferred gain and bandwidth characteristics by appropriate selection of the wavelength and power characteristics of the pump signals, P_1 and P_2. It is relatively easy to modify the gain and bandwidth characteristics of the Raman amplifier 14 in this manner. This technique mitigates the drawback of the high pump power requirement of the Raman amplifier 22.

Moreover, the wavelength of the pump signals may be selected such that the gain of the Raman amplifier complements the gain of the Er amplifier at longer wavelengths, yet the pump signals can still be recycled through signal path 28 to pump the Er fiber in the second amplifier stage 22. For example, if the amplifier 22 had a gain characteristic which linearly decreased for signals having wavelengths between 1550 nm and 1570 nm, then the wavelengths of the pump signals P_1, P_2 could be selected to provide the Raman amplifier 14 having a gain characteristic which increased linearly

between wavelengths of 1550 nm and 1570 nm. Thus, the hybrid Raman amplifier/Er power amplifier configuration of optical amplifier 10 utilizes the advantages of each amplifier type to provide a relatively wide band, high gain, high power amplifier 10.

A still further improvement can be obtained by using a dispersion compensating fiber for the Raman gain fiber. Dispersion compensating fibers are well-known and can be used to reverse the dispersion of pulses caused by passage through conventional optical fibers.

If the second stage Er fiber is a fluoride fiber, it will provide gain at relatively long wavelengths and cause the amplifier 10 to have a wider bandwidth than it would have of a silica fiber were used in the second stage amplifier 22.

In accordance with another embodiment, pump signals P_1, P_2 are designed to have wavelengths of 1465 nm and 1485 nm, respectively. In this case, the composite gain spectrum of amplifier 10 may be wider and flatter than gain spectrums of conventional amplifiers. Thus, using the techniques of the present invention, an optical amplifier having a gain bandwidth in excess of 40 nm may be provided.

A pump source (not shown) which provides pump signals P_1 P_2 could be a Raman fiber laser which generates an output signal having a wavelength typically of about 1480 nm. Alternatively, the pump source may be provided from two high-power laser diodes, each of which provides a signal having different output wavelengths in the band of 1420 nm to 1520 nm. The selection of a particular type of pump source depends upon a variety of factors including, but not limited to, the total output power desired from the optical amplifier 10.

FIG. 2 illustrates another embodiment in which the first amplifier stage 14 is a rare earth doped fiber amplifier and the second amplifier stage 22 is a Raman amplifier. The pumping arrangements are the same as shown in FIG. 1. This arrangement has similar properties to the amplifier shown in FIG. 1 but may have a better noise figure. The gain spectra of the amplifiers shown in FIGs. 1 and 2 are illustrated in FIG. 3 which shows the overlap in the spectra which can be obtained in accordance with one

embodiment of the invention. In particular, the gain spectrum of the erbium amplifier extends from about 1530 nm to 1560 nm whereas the gain spectrum of the Raman amplifier can be adjusted to span from 1560 nm to 1580 nm. The result is a wider overall gain spectrum.

FIG. 4 is a block diagram of an optical amplifier constructed in accordance with the principles of the present invention in which both the first amplifier stage and the second amplifier stage are rare earth doped fiber amplifiers. Specifically, the first amplifier stage 30 is a fiber amplifier with a thulium doped ZBLAN core and the second stage 22 is an erbium/ytterbium doped fiber amplifier. The amplifier is pumped with pump signals 32 having a single frequency of 1.06 μm. The gain spectrum of such an amplifier is illustrated in FIG. 5. The thulium doped amplifier gain spectrum 500 is centered at 1.48 μm whereas the erbium/ytterbium spectrum 502 is centered at 1.55 μm. There is no overlap between the two spectra.

FIG. 6 is a block diagram of another optical amplifier constructed in accordance with the principles of the present invention in which the first amplifier stage 34 is a fiber amplifier with a praseodymium doped ZBLAN core and the second stage 22 is an erbium/ytterbium doped fiber amplifier. The amplifier is pumped with pump signals 36 having a single frequency of 1.04 μm. The gain spectrum of such an amplifier is illustrated in FIG. 7. The thulium doped amplifier gain spectrum 700 is centered at 1.3 μm whereas the erbium/ytterbium spectrum 702 is centered at 1.55 μm. There is no overlap between the two spectra.

FIG. 8 illustrates still another embodiment of the invention in which an erbium amplifier 804 is coupled to a Raman amplifier 814. Specifically, the amplifier has an input port 800 which is connected, via an isolator 802, to the erbium amplifier 804. The signal output of the erbium amplifier 804 is connected by means of a first wave division multiplexer (WDM) 804, a second isolator 808 and a second WDM 810 to the signal input of Raman amplifier 814. The signal output of amplifier 814 is connected to output port 818 via WDM 816. Pump signals 820, for example, at 1480 nm, are applied via WDM 816 to the system and propagate in a direction opposite to the input signals in Raman amplifier 814.

The excess pump signal which remains after pumping Raman amplifier 814, is bypassed around isolator 808 by means of WDMS 810 and 804 and pumps erbium amplifier 804. The pump signal also propagates in a direction opposite to the input signals in amplifier 804. Although a single pumping frequency is shown in FIG. 8, two different frequencies can be used as described above.

Having described preferred embodiments of the invention, it will now become apparent to one of ordinary skill in the art that other embodiments incorporating their concepts may be used. For example, it should be noted that while, in a preferred embodiment, amplifier 10 includes isolator 20, in some applications isolator 20 may be omitted from amplifier 10. The removal of isolator 20 allows the excess pump signal counter-propagating through Er amplifier 22 to continue propagating through WDM 16 and into Raman amplifier 14. In general, this excess pump signal will adversely impact the noise performance of Raman amplifier 14, but, in some circumstances this will be acceptable. Similarly, removal of multistage isolator 20 may cause WDM 24 to receive back reflections from components coupled to amplifier output port 10b.

In addition the inventive multistage amplifier can be used in combination with other amplifiers. For example, the disclosed Raman/erbium-doped amplifier can be used as the second and third stage of a three stage amplifier. The erbium first stage can be coupled to the Raman/erbium-doped amplifier by an isolator.

While the invention has been shown and described above with respect to various preferred embodiments, it will apparent that the foregoing and other changes of the form and detail may be made therein by one skilled in the art without departing from the spirit and scope of the invention. These and other obvious modifications are intended to be covered by the following claims.

What is claimed is:

1. An at least two stage fiber amplifier comprising:

a first stage fiber amplifier having an first end and a second end;

a second stage fiber amplifier having a first end optically coupled to the second end of the first stage fiber amplifier and a second end;

a pump source optically coupled to the first stage fiber amplifier second end for providing to the first stage fiber amplifier a pumping signal which pumps the first stage fiber amplifier as it propagates to the first stage fiber amplifier first end; and

an optical fiber optically coupling the first stage fiber amplifier first end to the second stage fiber amplifier so that unabsorbed pump signal at the first stage fiber amplifier first end is is applied to the second stage fiber amplifier to pump the second stage fiber amplifier.

2. The at least two stage fiber amplifier of claim 1 wherein an input signal is provided to the first stage fiber amplifier first end and propagates to the first stage fiber amplifier second end for amplification, wherein the pump signal propagates in a direction opposite to the input signal.

3. The at least two stage fiber amplifier of claim 1 wherein the first stage fiber amplifier is a Raman amplifier.

4. The at least two stage fiber amplifier of claim 3 wherein the Raman amplifier has a dispersion compensating fiber core.

5. The at least two stage fiber amplifier of claim 1 wherein the second stage fiber amplifier has a rare earth doped fiber core.

6. The at least two stage fiber amplifier of claim 4 wherein the first stage fiber amplifer has a rare earth doped fiber core.

7. The at least two stage fiber amplifier of claim 5 wherein the first stage fiber amplifier has a thulium doped ZBLAN core and the second stage fiber amplifier has an erbium/ytterbium doped fiber core.

8. The at least two stage fiber amplifier of claim 5 wherein the first stage fiber amplifier has a praseodymium doped ZBLAN core and the second stage fiber amplifier has an erbium/ytterbium doped fiber core.

9. An at least two stage fiber amplifier comprising:
   a first stage fiber amplifier operating within a first spectrum band; and
   a second stage fiber amplifier operating within a second spectrum band different from the first spectrum band.

10. The at least two stage fiber amplifier of claim 9 wherein the first and second spectrum bands partially overlap.

11. The at least two stage fiber amplifier of claim 9 wherein the first and second spectrum bands are adjacent and have substantially no overlap.

12. The at least two stage fiber amplifier of claim 9 wherein the first and second spectrum bands do not overlap.

13. The at least two stage fiber amplifier of claim 9 wherein the first and the second stage fiber amplifiers are pumped with pump radiation from a single pump source.

14. The at least two stage fiber amplifier of claim 9 wherein the first and the second stage fiber amplifiers are both pumped with pump radiation from more than one pump source.

15. The at least two stage fiber amplifier of claim 9 wherein the first and the second stage fiber amplifiers are fiber Raman amplifiers.

16. The at least two stage fiber amplifier of claim 9 wherein the first stage fiber amplifier comprises at least two Raman fiber amplifiers.

17. The at least two stage fiber amplifier of claim 9 wherein the second stage fiber amplifier comprises a rare earth doped fiber amplifier.

18. An optical fiber amplifier unit comprising:

a first optical fiber amplifier having a Raman gain medium; and

a second optical fiber amplifier coupled to the first optical fiber amplifier, the second optical fiber amplifier having an active gain medium comprising one or more rare earth materials.

19. The optical fiber amplifier unit of claim 18 wherein the first and the second optical fiber amplifiers are pumped by a single pump source.

20. The optical fiber amplifier unit of claim 19 wherein the first optical fiber amplifier is series coupled to the second optical fiber amplifier and is optically coupled to the second optical fiber amplifier via a third optical fiber, the pump source being directly coupled to the first optical fiber amplifier for pumping and being coupled to the second optical fiber amplifier via the third optical fiber for pumping.

21. An optical fiber amplifier unit comprising:

a first low-noise optical fiber amplifier; and

a second high power output optical fiber amplifier coupled in series to the first optical fiber amplifier.

22. The optical fiber amplifier unit of claim 21 wherein the first optical fiber amplifier has a Raman gain medium.

23. The optical fiber amplifier unit of claim 22 wherein the Raman gain medium is selected to provide a wide gain bandwidth.

24. A multistage optical amplifier unit comprising at least two optical fiber amplifiers connected in series wherein the output of one stage provides input for another stage; the amplifiers characterized by having different types of gain mechanisms with pumping excitation provided from at least one pump source.

25. The optical fiber amplifier unit of claim 24 wherein the stimulated gain mechanism in one of the at least two optical fiber amplifiers is a Raman gain mechanism and the gain mechanism in one of the at least two optical fiber amplifiers is an active rare earth dopant in its fiber core.

26. An optical amplifier unit for amplifying an input signal comprising:

a first stage fiber amplifier comprising a Raman amplifier for receiving the input signal;

a high power pump source providing pumping power for the Raman amplifier;

a second stage fiber amplifier comprising an active dopant medium; and

two optical coupling paths formed between the first and second stage fiber amplifiers, the first coupling path connecting the first and the second stage fiber amplifiers for providing the input signal as an input to the second stage fiber amplifier from an output of the first stage fiber amplifier and the second coupling path providing for transfer of excess of the pumping power from the first stage fiber amplifier to the second stage fiber amplifier for pumping the second stage fiber amplifier.

27. The optical amplifier unit of claim 26 wherein the high power pump source comprises a plurality of pump sources, each having an output and a wave division multiplexer for combining the pump source outputs together for input to the first stage fiber amplifier.

28. The optical amplifier unit of claim 27 wherein each of the plurality of pump sources is a laser diode having an output wavelength within the absorption bands of the first and second stage fiber amplifiers.

29. The optical amplifier unit of claim 27 wherein each of the plurality of pump sources comprises a fiber laser.

30. An optical amplifier unit for amplifying an input signal, the amplifier unit comprising:

a first stage fiber amplifier for receiving the input signal, the first stage fiber amplifier having a first gain bandwidth;

a pump source providing pumping power to the first stage fiber amplifier; and

a second stage fiber amplifier having an input coupled to receive the output of the first stage fiber amplifier and having a second gain bandwidth wherein the overall gain of the optical amplifier unit is substantially uniform over a system bandwidth which is wider than the first and second gain bandwidths.

31. The optical amplifier unit of claim 30 wherein the first stage fiber amplifier comprises a Raman amplifier.

32. An optical amplifier unit for amplifying an input signal comprising:

a fiber amplifier comprising a Raman amplifier for receiving the input signal; and

at least two pump sources providing pumping power to the Raman amplifier at two different, spatially separated wavelengths to develop separate Raman gain spectra in the fiber amplifier.

33. The optical amplifier unit of claim 32 further comprising:

a second stage fiber amplifier comprising a fiber core with an active dopant in the fiber core; and

two optical coupling paths formed between the first and second stage fiber amplifiers, the first coupling path between the first stage fiber amplifier and the second stage fiber amplifier providing the input signal as an input to the second stage fiber amplifier from an output of the first stage fiber amplifier and the second coupling path providing for transfer of pumping power from the first stage fiber amplifier to the second stage fiber amplifier for pumping the second stage fiber amplifier, wherein the combination of the dual gain spectra of the Raman amplifier and the second stage fiber amplifier providing for a total gain spectrum for the optical amplifier unit over a bandwidth of tens of nanometers.

34. An optical amplifier having an input port and an output port comprising:

a first wave division multiplexer having a first input port coupled to the input port of the optical amplifier and having a second port;

a first fiber Raman amplifier stage having a first port coupled to the second port of the first wave division multiplexer and having a second port;

a second wave division multiplexer having a first port, a second port and a third port with the first port of the second wave division multiplexor coupled to the second port of the first amplifier stage;

a second amplifier stage having a first port coupled to the second port of the second wave division multiplexer the second stage fiber amplifier provided from a single mode optical fiber section that includes a rare earth doped core;

a third wave division multiplexer having a first port, a second port and a third port with the first port of the second wave division multiplexor coupled to the second port of the second amplifier stage

and the second port of the third wave division multiplexer coupled to the output port of the optical amplifier; and

a signal path coupled between the third port of the first wave division multiplexer to the third port of the third wave division multiplexer.

35. The optical amplifier of claim 34 further comprising a first isolator having a first port coupled to the second port of the second wave division multiplexer and having a second port coupled to the input port of the second stage fiber amplifier.

36. The optical amplifier of claim 35 further comprising a second isolator having a first port coupled to the second port of the third wave division multiplexer and an output port coupled to the output port of the optical amplifier circuit.

37. The optical amplifier of claim 36 wherein the second stage fiber amplifier comprises one of:

a silica fiber; and

a fluoride fiber.

38. The optical amplifier of claim 37 further comprising a pump source having an output port coupled to the third port of the first wave division multiplexer.

39. The optical amplifier of claim 36 further comprising a fourth wave division multiplexer having a first input port and a second input port and having an output port coupled to the third input port of the second wave division multiplexer.

40. The optical amplifier of claim 39 further comprising a first pump source having a first port coupled to the first input port of the fourth wave division multiplexer.

41. The optical amplifier of claim 40 further comprising a second pump source having a first port coupled to the second input port of the fourth wave division multiplexer.

42. The optical amplifier of claim 41 wherein the first and second pump sources comprise one of:

a Raman fiber laser; and

a plurality of semiconductor laser diodes.

43. The optical amplifier of claim 42 wherein the pump source comprises a Raman fiber laser which emits a signal having a wavelength of 1480 nm.

44. The optical amplifier of claim 42 wherein the pump source comprises a pair of laser diodes, each of the laser diodes emitting a signal having a wavelength of 1480 nm.

45. The optical amplifier of claim 36 wherein the second isolator comprises a multistage isolator.

46. An at least two stage fiber amplifier comprising:

a first stage fiber amplifier having an first end and a second end;

a second stage fiber amplifier having a first end optically coupled to the second end of the first stage fiber amplifier and a second end;

a pump source optically coupled to the second stage fiber amplifier second end for providing to the second stage fiber amplifier a pumping signal which pumps the second stage fiber amplifier as it propagates to the second stage fiber amplifier first end; and

an optical fiber optically coupling the second stage fiber amplifier first end to the first stage fiber amplifier so that unabsorbed

pump signal at the second stage fiber amplifier first end is is applied to the first stage fiber amplifier to pump the first stage fiber amplifier.

47. The at least two stage fiber amplifier of claim 46 wherein the second stage fiber amplifier first end is optically coupled to the second end of the first stage fiber amplifier though an optical isolator.

48. The at least two stage fiber amplifier of claim 46 wherein the first stage fiber amplifier comprises a rare earth doped amplifer.

49. The at least two stage fiber amplifier of claim 48 wherein the second stage fiber amplifier comprises a Raman amplifier.

50. The at least two stage fiber amplifier of claim 49 wherein the Raman amplifer has a dispersion compensating fiber core.

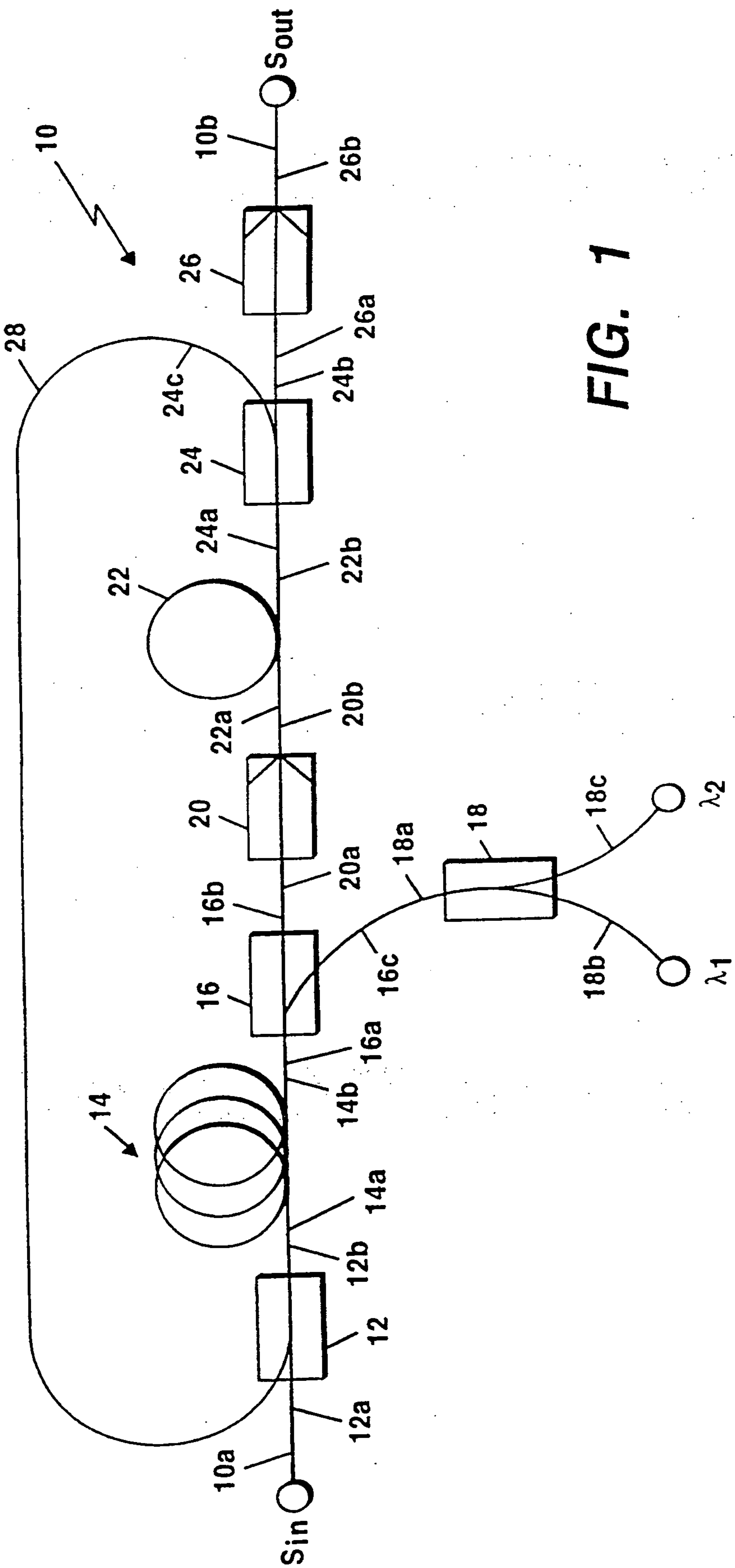

10
Sout
10b
26b
26
26a
28
24c
24b
24
24a
22
22b
22a
20b
20
20a
16b
18a
18
18c
λ2
16
16c
18b
λ1
16a
14
14b
14a
12b
12
12a
10a
Sin

FIG. 1

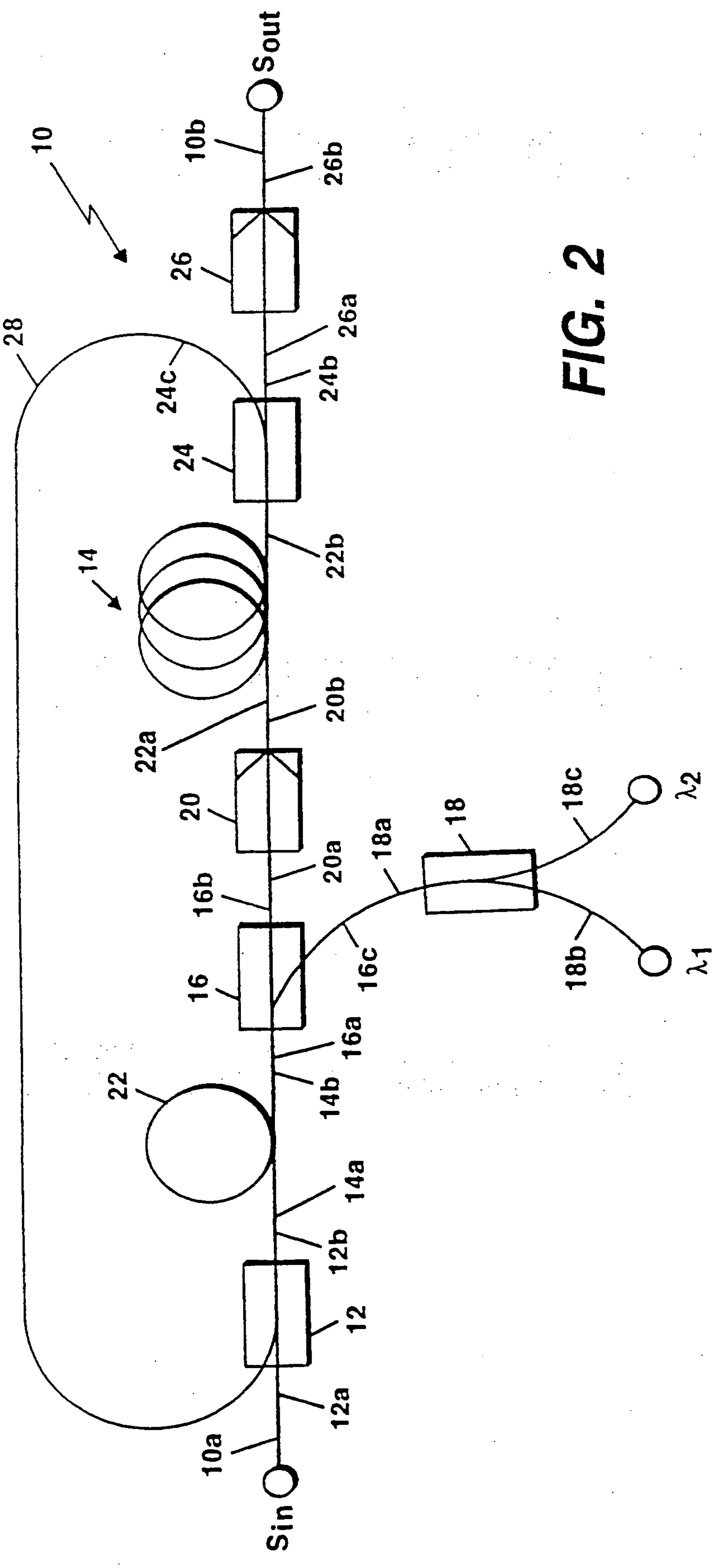

Sout
10
10b
26b
26
26a
24b
24c
24
28
14
22b
22a
20b
20
20a
16b
18a
18
18c
λ_2
16c
18b
λ_1
16
16a
22
14b
14a
12b
12
12a
10a
Sin

FIG. 2

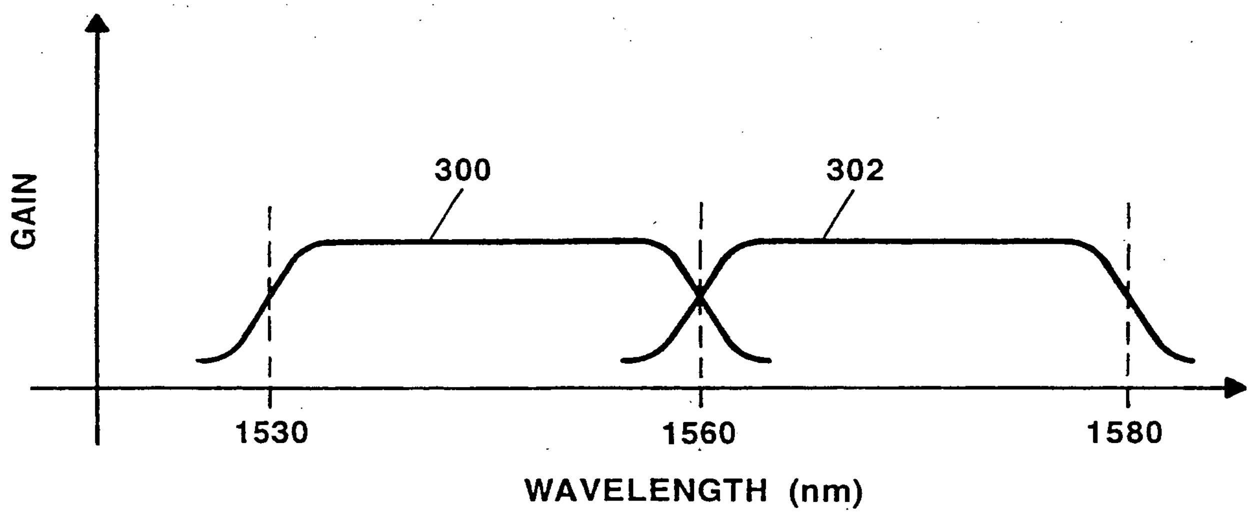

GAIN
300
302
1530
1560
1580
WAVELENGTH (nm)

FIG. 3

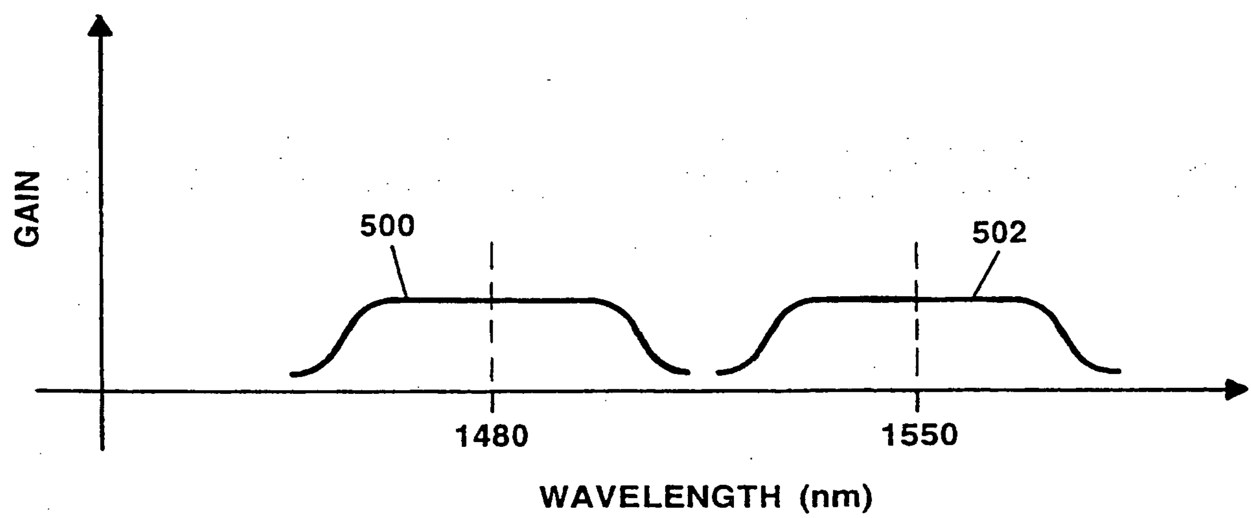
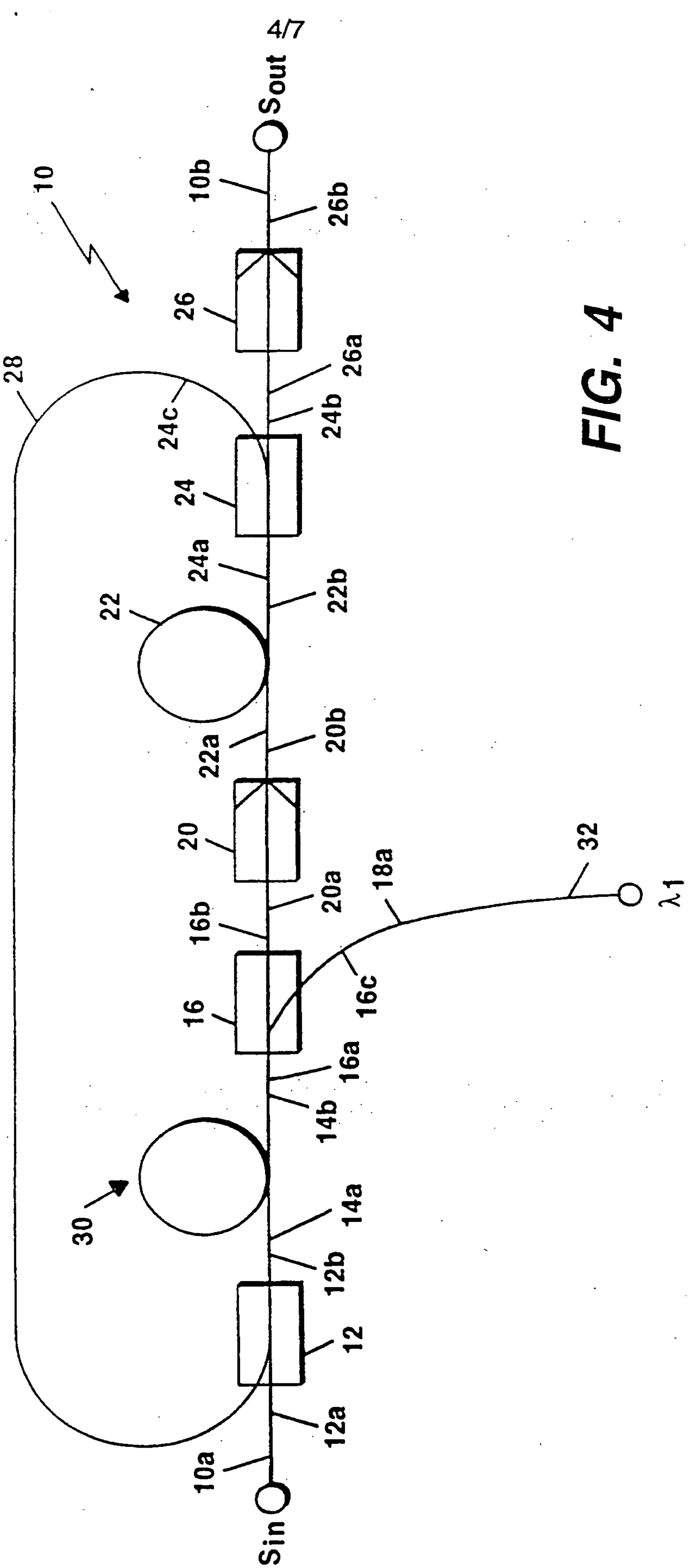

GAIN
500
502
1480
1550
WAVELENGTH (nm)

FIG. 5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28
24c
26
24
22
20
16
30
Sout
10b
26b
26a
24b
24a
22b
22a
20b
20a
16b
18a
32
λ1
16c
16a
14b
14a
12b
12
12a
10a
Sin

FIG. 4

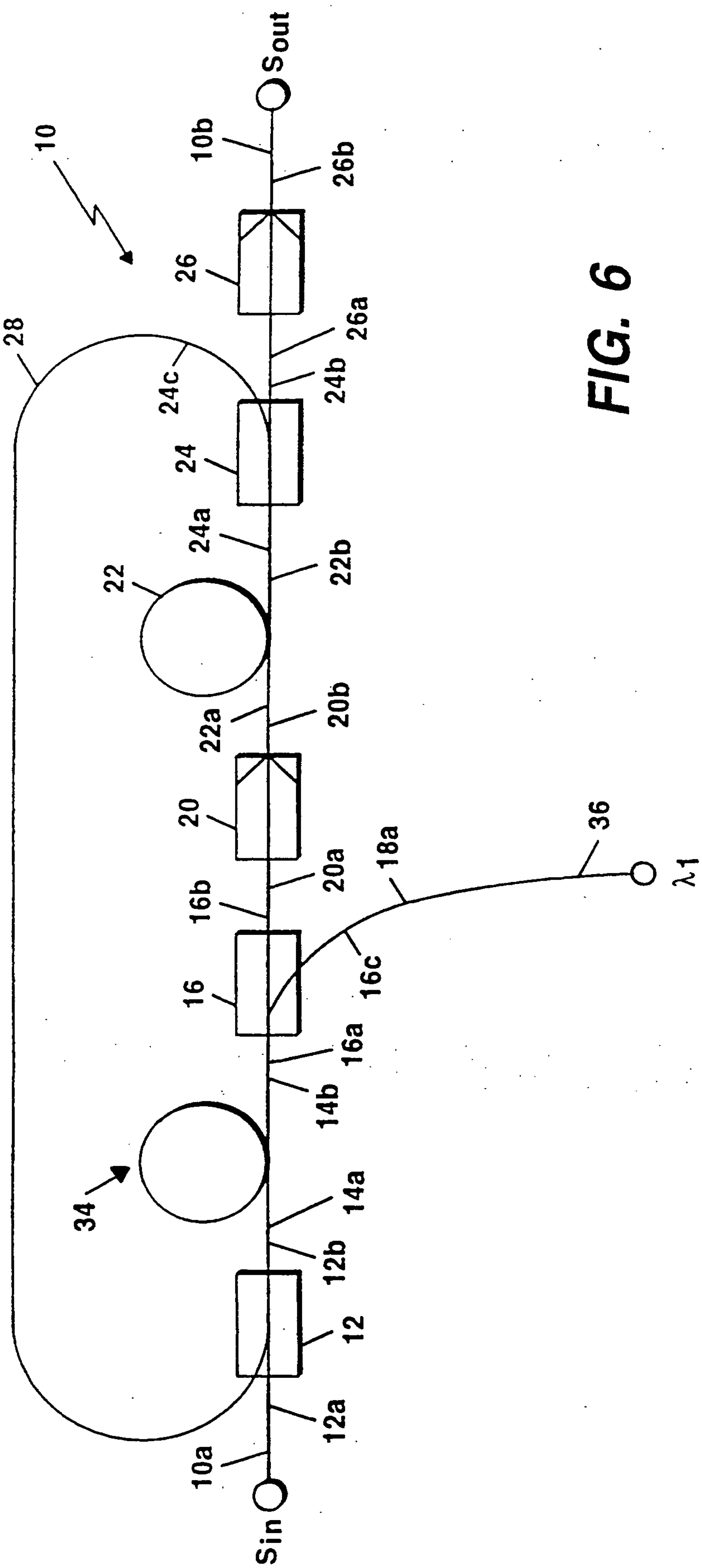
Sout
10
10b
26b
26
26a
28
24c
24b
24
24a
22
22b
22a
20b
20
20a
16b
18a
36
λ1
16
16c
16a
14b
34
14a
12b
12
12a
10a
Sin

FIG. 6

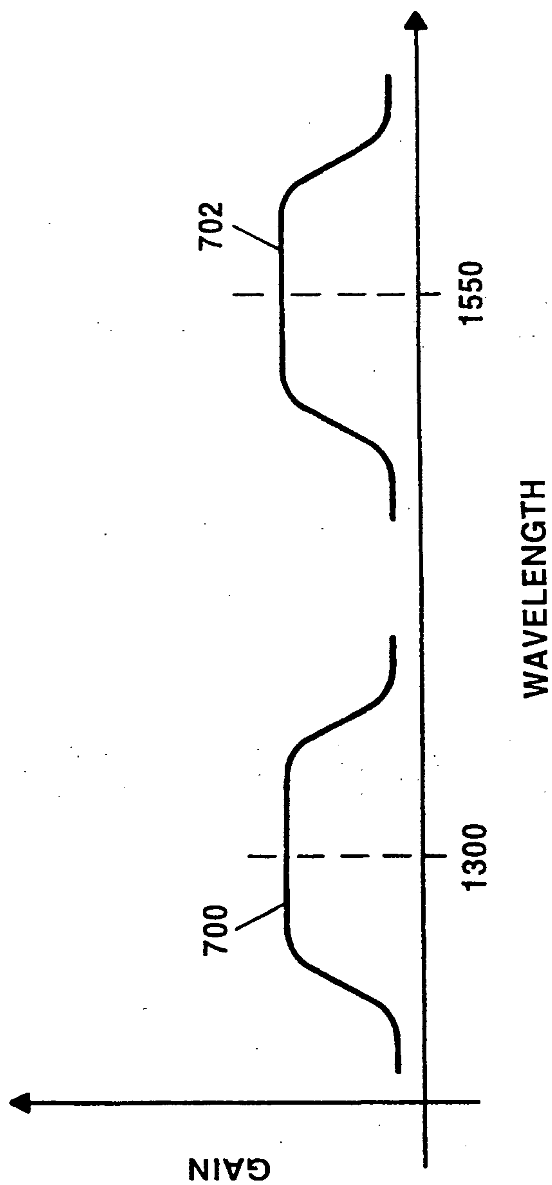

FIG. 7

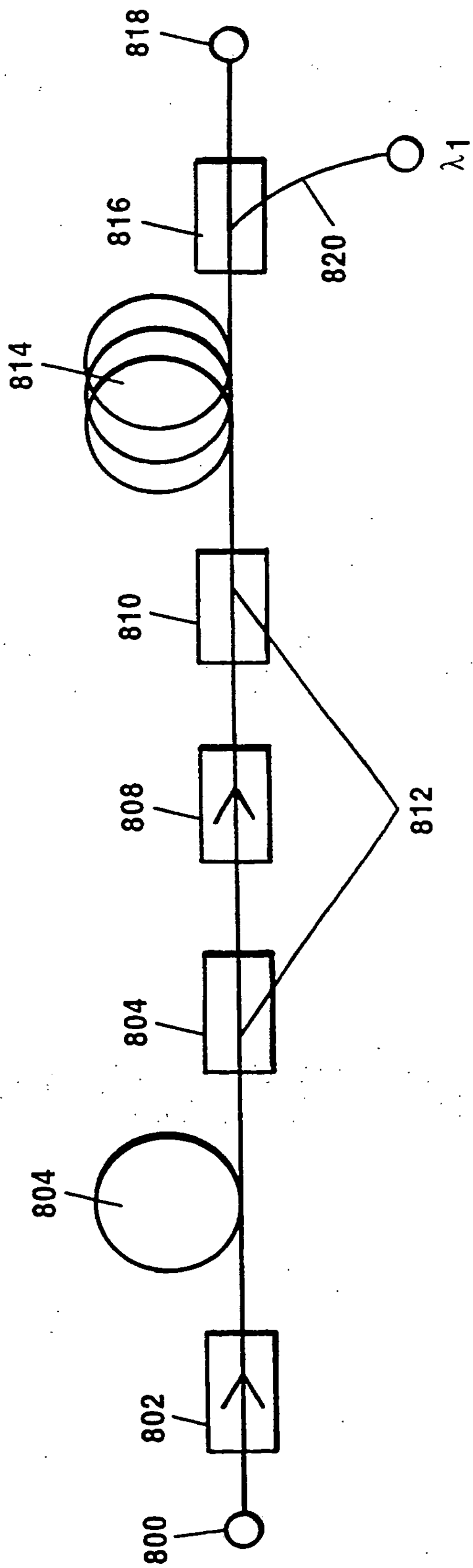

FIG. 8

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 98/04974

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H04B10/17 H01S3/06

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H04B H01S

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 506 723 A (JUNGINGER BERNHARD) 9 April 1996	1,2,5
Y	see abstract	3,7,8,13,18-20,26,34,35
	see column 1, line 20 - line 53	
A	see figure 1	33

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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Date of the actual completion of the international search	Date of mailing of the international search report
12 June 1998	19/06/1998

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Ribbe, A

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 98/04974

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	SEMENKOFF M ET AL: "HIGH POWER, HIGH GAIN OPTICAL FIBRE AMPLIFIER FOR MULTIWAVELENGTH TRANSMISSION SYSTEMS" ELECTRONICS LETTERS, vol. 30, no. 17, 18 August 1994, pages 1411-1413, XP000476033 see abstract see page 1411, right-hand column see page 1412, left-hand column	7,8
A	see figure 1	37
A	US 5 530 583 A (UNO TOMOAKI ET AL) 25 June 1996 see column 10, line 20 - line 27	7,8
X	AIDA K ET AL: "DESIGN AND PERFORMANCE OF A LONG-SPAN IM/DD OPTICAL TRANSMISSION SYSTEM USING REMOTELY PUMPED OPTICAL AMPLIFIERS" IEE PROCEEDINGS J. OPTOELECTRONICS, vol. 137, no. 4, 1 August 1990, pages 225-229, XP000148979	24,25
Y	see page 225, left-hand column, line 1 - right-hand column, line 6	3,18-20, 22,26, 31,34, 35,49
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Y	see column 1, line 58 - column 2, line 19 see column 4, line 20 - line 43	13,15,31
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A	see figure 1	16
X	EP 0 647 000 A (AT & T CORP) 5 April 1995 see abstract	21,46-48
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International Application No
PCT/US 98/04974

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